

Techno-economic appraisal of a dish/stirling solar power plant in Greece based on an innovative solar concentrator formed by elastic film

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ABSTRACT

As the environmental problems caused by the use of conventional fuels have risen significantly and due to the increase in fossil fuel prices, the importance of reducing society dependence on non-renewable energy sources becomes more and more urgent. It is clear that this could only happen by switching to extensive use of clean energy sources such as renewable energy sources. In this paper a technical feasibility and economic viability study of a dish/Stirling solar power plant in Greece is presented. The proposed power plant uses Dish/Stirling technology and has nominal power 10 MW. The proposed solar concentrator system consists of a primary mirror, formed by elastic film, used to focus the sun's rays onto a secondary mirror which then deviates this radiation into the receiver (Stirling engine). TRNSYS program was developed to simulate Dish/Stirling power plant operation in order to investigate its performance in Greece. The simulation predicted that the proposed power plant could produce 11.19 GWh annually. Project investment cost is approximately 27,000,000 €, while payback is achieved after 16 years of operation. The total profit at the end of the analysis period of 25 years is estimated to be 25,500,000 €.

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1. Introduction

During the last few decades, growing demand for energy and increasing environmental problems have intensified the research on clean energy and new technologies that will reduce pollution. For the current situation most of the renewable energy investigations concentrate on solar energy. Despite that solar energy is investigated for a large number of purposes, the prime objective is the electricity generation.

Higher temperatures and better efficiencies are achieved if the sunlight is concentrated before the conversion to heat takes place. There are several optical systems for concentration of sunlight for power production. Solar thermal technologies like parabolic trough, central tower and parabolic dish are under continual development in order to investigate and improve their future potential in total world energy consumption.

Dish/Stirling engine systems convert the thermal energy of solar radiation to mechanical energy and then to electrical energy.

The concentrator for the Dish/Stirling systems uses parabolic mirrors mounted on a structure that tracks the sun by pivoting on two axes. Concentrators use a reflective surface of aluminum or silver, deposited on glass or plastic. The most durable reflective surfaces have

been silver/glass mirrors, which solar reflectance ranges between 91 and 95% for current systems. Attempts to produce low cost reflective polymer films have had limited success in the past. The most innovative parabolic mirrors use stretched membranes where the reflective membrane is stretched across a hoop or rim and a second membrane is placed behind the first. A partial vacuum then pulls the first membrane into a parabolic shape [1].

The concept of stretched-membrane dish concentrators, currently under proof-of-reliability testing, holds great promise for further cost reduction in order to make them competitive with Diesel stations in remote areas or in islands. A variety of stretched-membrane dish concentrators designs have been proposed by the scientific community particularly in reference to space applications.

The receiver absorbs energy reflected by the concentrator and transfers it to the engine's working fluid, usually helium or hydrogen. A Stirling engine receiver consist of an aperture and an absorber. The aperture is located at the focal point of the parabolic concentrator to reduce radiation and convection heat losses. The fraction of the energy from the collector that enters the aperture, known as intercept factor, is often between 90 and 99% [6]. There are two general types of Stirling receivers: direct illumination receivers, that adapt the heater tubes of the Stirling engine, and indirect receivers, which use an intermediate heat-transfer fluid. Stirling receivers are typically about 90% efficient in transferring energy delivered by the concentrator to the engine.

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The Stirling engine converts the absorbed thermal energy to mechanical power by expanding the working gas in a piston-cylinder in a manner similar to conventional engine. In the Stirling thermodynamic cycle, the working gas is alternately heated and cooled by constant-temperature and constant-volume processes. The mechanical power is then converted to electrical power by an electric generator [1,2].

In this paper Dish/Stirling technology is used in order to investigate a potential installation of a 10 MW concentrating solar thermal power plant in the island of Crete, Greece.

2. Methodology

TRNSYS program was used to simulate Dish/Stirling power plant in order to investigate its performance in Greece. TRNSYS is a flexible tool designed to simulate the transient performance of thermal energy systems [3]. The principle philosophy behind TRNSYS is a method of describing each physical component and energy system as a Fortran subroutine having inputs and outputs. The functional relations between inputs and outputs are defined in each subroutine. To create a system model, the user simply connects the outputs of components with the inputs of other components. A variety of utility components help to handle input from data files, generate forcing functions, print, plot, integrate or interpolate data.

2.1. Simulation of solar thermal power plant

TRNSYS major field of application is the evaluation of solar systems for heating and cooling purposes and domestic hot water applications. However, a growing group of engineers world wide are interested in other applications and solar systems, like solar thermal power systems. Because of its inherent flexibility, nowadays it is also actively being used in building simulation, hydrogen fuel cell systems, wind and photovoltaic systems, geothermal heat pump systems, and power plants (biomass, cogeneration). As neither TRNSYS 16 library of 80 standard components, nor add on libraries such as Solar Thermal Electric Components (STEC) library include components about Dish/Stirling systems, a very useful

feature of TRNSYS was used. This feature is the ability to insert equations that could describe the operation of the Dish/Stirling system. Each equations component can be linked to the outputs and inputs of other components as if it were a normal component. These equations components, which icon is a calculator, can be shown in Fig. 1 where the assembly of the system is represented. Except for these components, TRNSYS standard components like Type109-TMY2, Type89d (weather data readers), Type24 (quantity integrator) and Type65d (online plotter) are also used as in Fig. 1.

The weather data readers serve the purpose of reading weather data at regular time intervals from a data file, in the standard TMY2 format, converting it to a desired system of units. The TMY2 format is used by the National Solar Radiation Data Base (USA) but TMY2 files can be generated from many programs, such as Meteonorm [4].

With regard to simulation of system operation, mathematical equations were used to describe conversion of thermal energy to mechanical energy and then to electrical energy [2]. The parabolic concentrator equation (Pin_rec) calculates the solar power intercepted by the receiver based on direct normal radiation, as input from Type89d:

$$P_{in, rec} = I_{DNI} \cdot A_{proj} \cdot \rho_{ref} \cdot \phi_{int, fac} \quad (1)$$

where I_{DNI} is the direct normal radiation, A_{proj} the projected surface of the collector, ρ_{ref} the collector reflectivity and $\phi_{int, fac}$ is the intercept factor.

The receiver equation (Pin_SE) computes the thermal input power to the Stirling engine. It receives its energy input from the output of the collector equation. The input energy is diminished by radiation, convection, and conduction losses from the receiver (Q_{total}), which are location and time of day dependent:

$$P_{in, SE} = P_{in, rec} - q_{total} \quad (2)$$

$$q_{total} = q_{conv, tot} + q_{rad, emit} + q_{rad, refl} + q_{cond} \quad (3)$$

The conduction losses through the receiver housing to the ambient air are minimal and are dependent on the receiver temperature, insulation thickness and conductivity, and the ambient

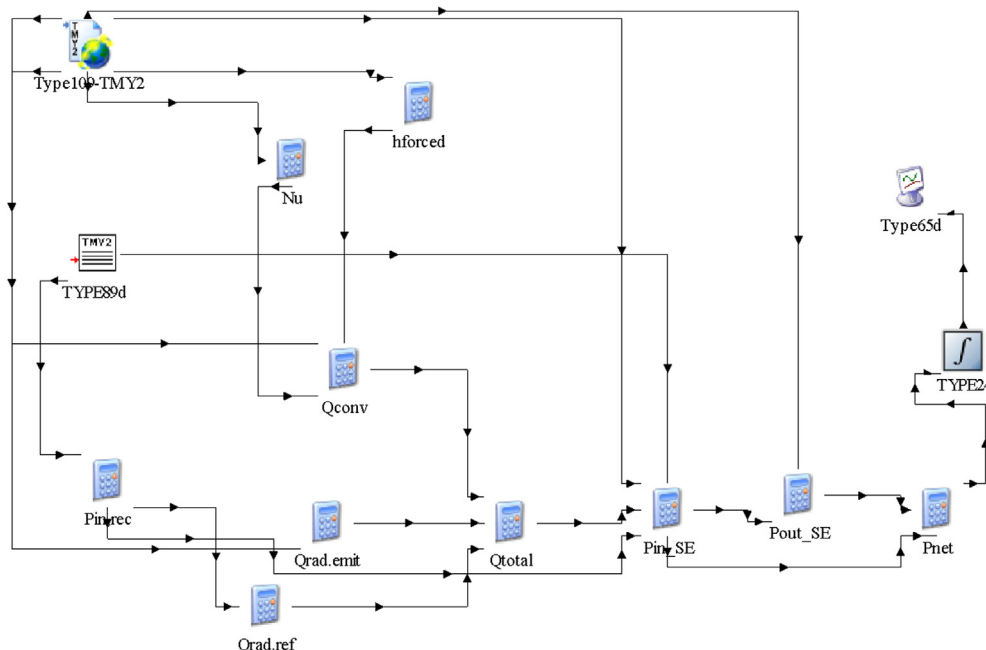


Fig. 1. TRNSYS assembly of power plant.

temperature. In this study conduction losses are assumed to be constant in total losses equation. The convection losses, calculated by convection equation ($q_{conv, tot}$), represent a large fraction of the receiver losses and depend on the ambient temperature, wind velocity, receiver cavity temperature, and orientation of the receiver aperture. Convection losses will be greater when the elevation angle of the sun is lower during the morning, evening and winter:

$$q_{conv, tot} = h_{total, convection} \cdot A_{cav} \cdot (T_{cav} - T_{amb}) \quad (4)$$

$$h_{total, convection} = h_{natural} + h_{forced} \quad (5)$$

where $h_{natural}$ is the natural convection coefficient which is determined from the Nusselt number assuming the interior cavity diameter parallel to the aperture as the characteristic length, h_{forced} is the forced convection coefficient which depends on wind velocity, A_{cav} the total surface area of the cavity interior, T_{cav} the average temperature of the interior cavity walls and T_{amb} is the ambient temperature.

The radiation losses include long-wave radiation emission (Qrad.emit) out of the aperture resulting from the high temperature of the cavity walls, and reflected radiation (Qrad.ref) of the cavity walls and out of the receiver aperture since the interior cavity is not an effective black body:

$$q_{rad, emit} = \varepsilon \cdot A_{ap} \cdot \sigma \cdot (T_{cav}^4 - T_{amb}^4) \quad (6)$$

$$q_{rad, ref} = (1 - a_{eff}) \cdot P_{in, rec} \quad (7)$$

where ε is the emissivity of the cavity, A_{ap} the surface area of the receiver aperture opening, σ the Stefan–Boltzmann constant and a_{eff} is the effective absorptance of the cavity.

The Stirling engine equation (Pout.SE) calculates the gross output power of the engine while the net system power (Pnet) is found by subtracting the parasitic power of the tracking and controls, pump, and fan from the gross output power of the engine.

$$P_{gross} = Beale_{curve} \cdot (P_{mean} \cdot V_{SW} \cdot f \cdot T_{correct}) \quad (8)$$

$$Beale_{curve} = 0.0391 + 0.0000221 \cdot P_{in, SE} - 3.55 \times 10^{-10} \cdot P_{in, SE}^2 \quad (9)$$

$$T_{correct} = 1 - \left(\frac{T_C}{T_E} \right)^{0.5} \quad (10a)$$

where $Beale_{curve}$ is the Beale number including a temperature correction term $T_{correct}$, T_E is the expansion space temperature of the engine, T_C is the compression space temperature, P_{mean} is the mean engine pressure, V_{SW} is the swept volume of the engine, and f is the engine frequency.

Finally, in order to calculate the annual electrical energy production, Type24 standard component was used. This component, which is a quantity integrator, was used to integrate the net power over a period of a year. The results were extracted with a graphics component which is the online plotter Type65d. The flow chart of the sequence of calculations is given in Fig. 2.

2.2. Input data

2.2.1. Technical data

The proposed solar power plant has nominal power 10 MW and is considered to be installed in Crete. The total field area required

for the power plant is about 250,000 m², as the solar field area required for each unit is assumed to be 225 m² [5].

The proposed solar concentrator consists of hermetic volume confined by a thick rubber film (film thickness is ~10 mm). The volume is attached to rigid tube armature (Fig. 3) and the pressure difference will form a concave profile that will be a base for concentrator flexible mirror film. Thin polymeric film with mirror layer will be glued on the rubber base. The film must be stretched before pumping to give additional rigidity to the concave surface (the tension in the film must be an order higher than the additional tension caused by wind load). This in turn will force the surface to become convex upwards. Then, the pumping pressure difference gives rubber film the downward convexity.

The tubular frame with diameter 10 m is produced. Two disk rings are produced from rubber sheet with thickness 10 mm. Inner diameters are 2 m and outer ones are 9 m. Cylindrical side surface with diameter 9 m and width 2 m is made of the same rubber sheet. Two rubber rings are put one on the other and glued together along the inner contours. Side surface is glued with the outer contours so that closed rubber chamber is formed. The glued places are vulcanized. Holes are made along the contour of glued seams and are strengthened by riveted metal tubes. Holes are used to attach the rubber rings to the armature by adjustable tension wire. The inner contour of rubber rings is in the same way attached to the tubular ring diameter of that is <2 m. Rubber rings are stretched by the tension wires to the diameter 10 m. For pumping the air out the connecting pipe is glued in the side surface. Air is pumped out the chamber so that pressure decreases by 5–10%. The result is controlled with the aid of laser beam reflected from a small test mirror laying on a concave surface. Sectors of mirror film are glued to the rubber surface by a special non-drying gel. Gel permits to avoid tension in the mirror film that can cause its hogging. Besides, it permits to change the mirror film that can become worthless due to atmospheric impact.

The possible geometric defects of the primary mirror can be corrected by a special form of secondary mirror forming a parallel light beam as seen in Fig. 4. The required concentration ratio is about 100 providing the working medium reaches 600–700 °C with the use of selective glass filters.

The proposed dish/Stirling solar power plant consists of 1000 units (as the one described above) of 10 kW each and the SOLO 161 Stirling power conversion unit (PCU). The concentrator uses an elevation-over-azimuth tracking space frame dish structure. The SOLO 161 Stirling PCU is an alpha configuration kinematic Stirling engine, which is being developed by Kleinmotoren for cogeneration and solar applications in Germany. It utilizes a direct illumination solar receiver and hydrogen as working fluid.

The Collector Control System (CCS) provides both control and monitoring of the concentrator and the PCU and allows autonomous system operation. After the system detects that DNI is within specifications, it tracks to acquire the sun, starts the PCU, and supplies power to the grid. If the anemometer detects high winds, the system automatically drives to stow where it remains until wind speed returns to a safe level for a specified period of time. When clouds are detected (low DNI), the system drives off sun and continues to offset track. When DNI returns to specified levels the system reacquires the sun and starts the PCU. If the sun does not return within a specified time, the concentrator stows [6]. In this study operational specifications are DNI greater than 350 W/m² and wind speed less than 15 m/s [8]. It is also assumed that availability is 94% [5]. Availability is defined as the time the system produces net positive power divided by the time insolation and wind are within operational specifications. This availability definition includes the time required while the system is slewing into focus and while warming up.

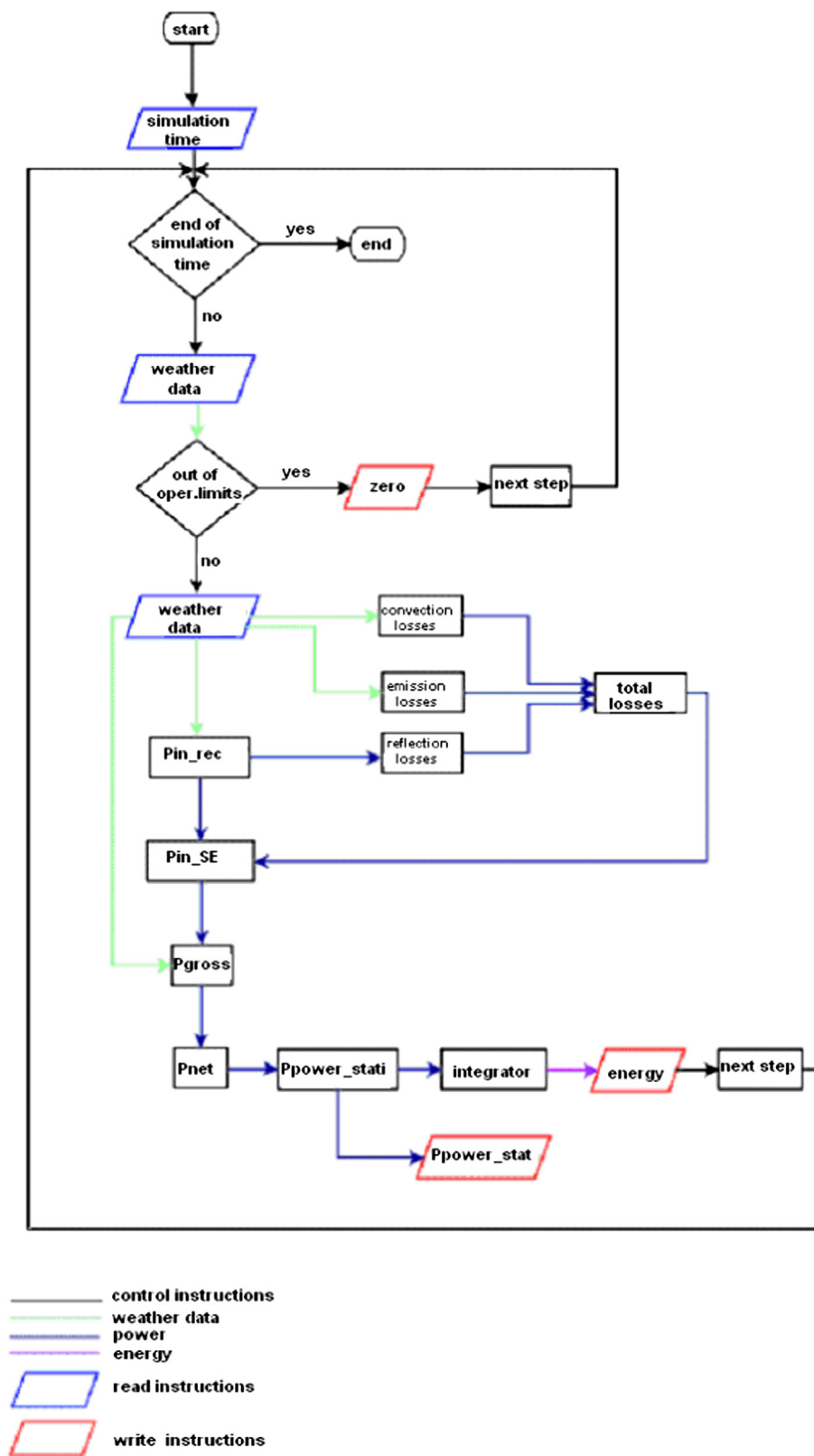


Fig. 2. Flow chart of the sequence of calculations.

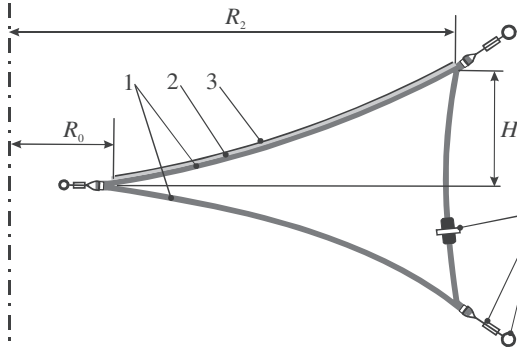


Fig. 3. Primary mirror components: (1)–rubber sheet; (2)–non-drying gel; (3)–mirror film; (4)–pump tube; (5)–adjustable tension wires; (6)–armature; (R_0)–inner radius; (R_2)–outer radius under tension.

2.2.2. Primary mirror form modeling

Taking under consideration the cylindrical coordinate system (r, ϕ, z), the initial shape of rubber film is a plane ring with inner radius R_0 and outer R_1 . Let's assume a point of film which initially has coordinates ($x, 0, 0$). Due to action of tension and pressure difference coordinates change to ($r, 0, z$). The shape acquired by film may be described by a parametric dependence as follows:

$$r = r(x), z = z(x); R_0 \leq x \leq R_1$$

Let's consider a differentially small element of surface, the quadrangle ABDC (Fig. 5), where vertexes satisfy the following conditions:

$$r_A = r_B = r, r_C = r_D = r + dr,$$

$$z_A = z_B = z, z_C = z_D = z + dz,$$

$$x_A = x_B = x, x_C = x_D = x + dx,$$

$$\phi_A = \phi_D = 0, \phi_B = \phi_C = d\phi,$$

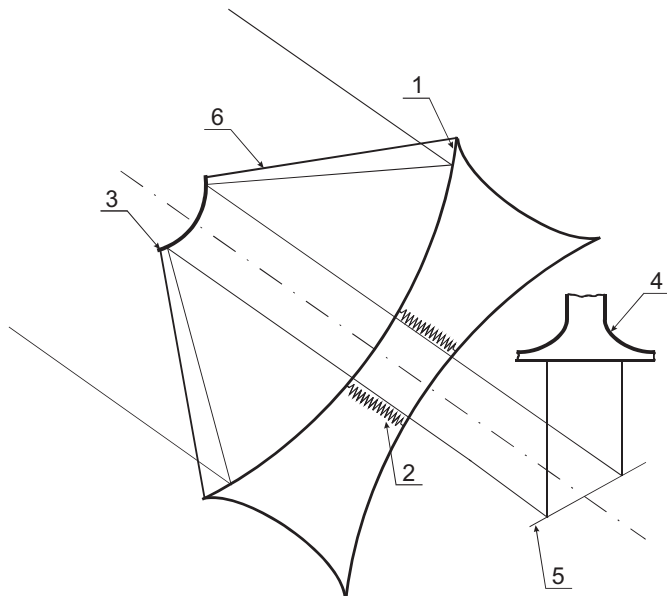


Fig. 4. Proposed solar concentrator: 1–primary mirror, 2–supporting springs, 3–secondary mirror, 4–receiver (Stirling engine), 5–reflective mirror, 6–supporting structure.

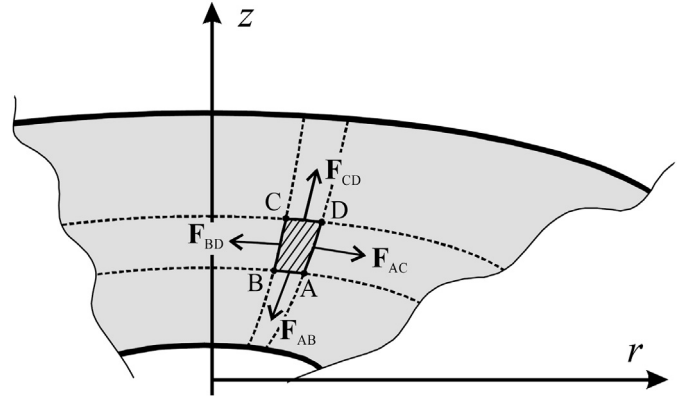


Fig. 5. For the formulation of force balance equations.

where x is, as before, the initial r coordinate of the film point. Let's consider as θ the angle of surface in points A and B, and $(\theta + d\theta)$ the angle in C and D.

As a rule, the deformation of rubber is connected with tension and bending. The characteristic value of relative deformation connected with bending is equal to the ratio of the film thickness (~ 1 cm) and the curvature radius (~ 10 m), which is less than the general value of relative deformation (~ 0.1). Therefore, the force moments due to film bending may be neglected and it can be considered that the forces applied to the borders of quadrangle are tangent to the surface.

Let's assume that there is a balance between the forces applied to the borders of quadrangle and the transverse force caused by pressure difference (Fig. 5). Let's denote the tension acting on the sides AB and CD as σ_l , and the tension acting on AD and BC as σ_t . The tensions are functions of x and the forces acting on the quadrangle borders are equal:

$$F_{AC} = F_{BD} = dl\delta\sigma_t = dr\delta\sigma_t/\cos\theta F_{AB} = rd\phi\delta\sigma_l,$$

$$F_{CD} = (r + dr)d\phi\delta(\sigma_l + d\sigma_l),$$

where δ is the rubber film thickness. The sum of forces $\mathbf{F}_{AC} + \mathbf{F}_{BD}$ is directed perpendicular to z axis and its absolute value is given as follows:

$$|\mathbf{F}_{AC} + \mathbf{F}_{BD}| = F_{AC} d\phi.$$

The tangent projection of the two other forces sum ($\mathbf{F}_{AB} + \mathbf{F}_{CD}$) is given below:

$$(\mathbf{F}_{AB} + \mathbf{F}_{CD})_{\parallel} = F_{CD} - F_{AB} = d\phi\delta(rd\sigma_l + \sigma_l dr),$$

and its normal projection is equal to:

$$(\mathbf{F}_{AB} + \mathbf{F}_{CD})_{\perp} = F_{AB}d\theta.$$

The balance of tangent projections leads to the following equation:

$$rd\sigma_l + \sigma_l dr - \sigma_t dl \cos\theta = 0, \quad (10b)$$

and the balance of normal projections leads to the equation:

$$\sigma_l \delta r d\theta + \sigma_t \delta \sin\theta dl - \Delta P r dl = 0. \quad (11)$$

The elasticity law gives the following relationships for the strained surface:

$$dl = (1 + \varepsilon_l)dx = (1 + (\sigma_l - \mu\sigma_t)/E)dx;$$

Table 1
Monthly energy production.

Month	Jan.	Febr.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
GWh	0.43	0.50	0.75	0.95	1.29	1.49	1.31	1.38	1.54	0.79	0.50	0.27

$$r/x - 1 = \varepsilon_t = (\sigma_t - \mu\sigma_l)/E,$$

where

$$dl = \sqrt{dr^2 + dz^2}; \quad dr = \cos \theta \, dl, \quad dz = \sin \theta \, dl$$

As a result, the following system of equations is produced for unknown parameters $r(x)$, $z(x)$, $\sigma_l(x)$, $\theta(x)$:

$$\begin{aligned} \frac{dr}{dx} &= (1 + \varepsilon_l)\cos \theta \\ \frac{dz}{dx} &= (1 + \varepsilon_l)\sin \theta \\ \frac{d\sigma_l}{dx} &= \frac{\sigma_t - \sigma_l}{r}\cos \theta \\ \frac{d\theta}{dx} &= \frac{\Delta P}{\delta\sigma_l}\cos \theta - \frac{\sigma_t}{r\sigma_l}\sin \theta \end{aligned} \quad (12)$$

where

$$\sigma_t = (r/x - 1)E + \mu\sigma_l,$$

$$\varepsilon_l = (\sigma_l - \mu\sigma_t)/E$$

The system of equation (12) is solved by Runge-Kutta method for the interval $R_0 \leq x \leq R_1$. When the inner radius of rubber ring is constant, two out of four needed boundary conditions are as follows:

$$r(R_0) = R_0, \quad z(R_0) = 0,$$

while the other two conditions are given below:

$$r(R_1) = R_2, \quad z(R_1) = H, \quad (13)$$

where R_2 and H are the outer radius and vertical size of strained rubber ring (see Fig. 4). This way, the values $\theta(R_0)$, $\sigma_l(R_0)$ can be determined and thus the values $r(R_1)$, $z(R_1)$ can be obtained as a result of numerical solution of system equation (12) satisfying the conditions (13).

2.2.3. Weather data

Weather data obtained using Meteonorm program for the region Akrotiri, northwest of Greek island Crete. At this location direct normal radiation has one of the highest values in Greece, with aggregate annual value 1790 kWh/m². Meteonorm is a meteorological database containing comprehensive climatological data for solar engineering applications at every location of the

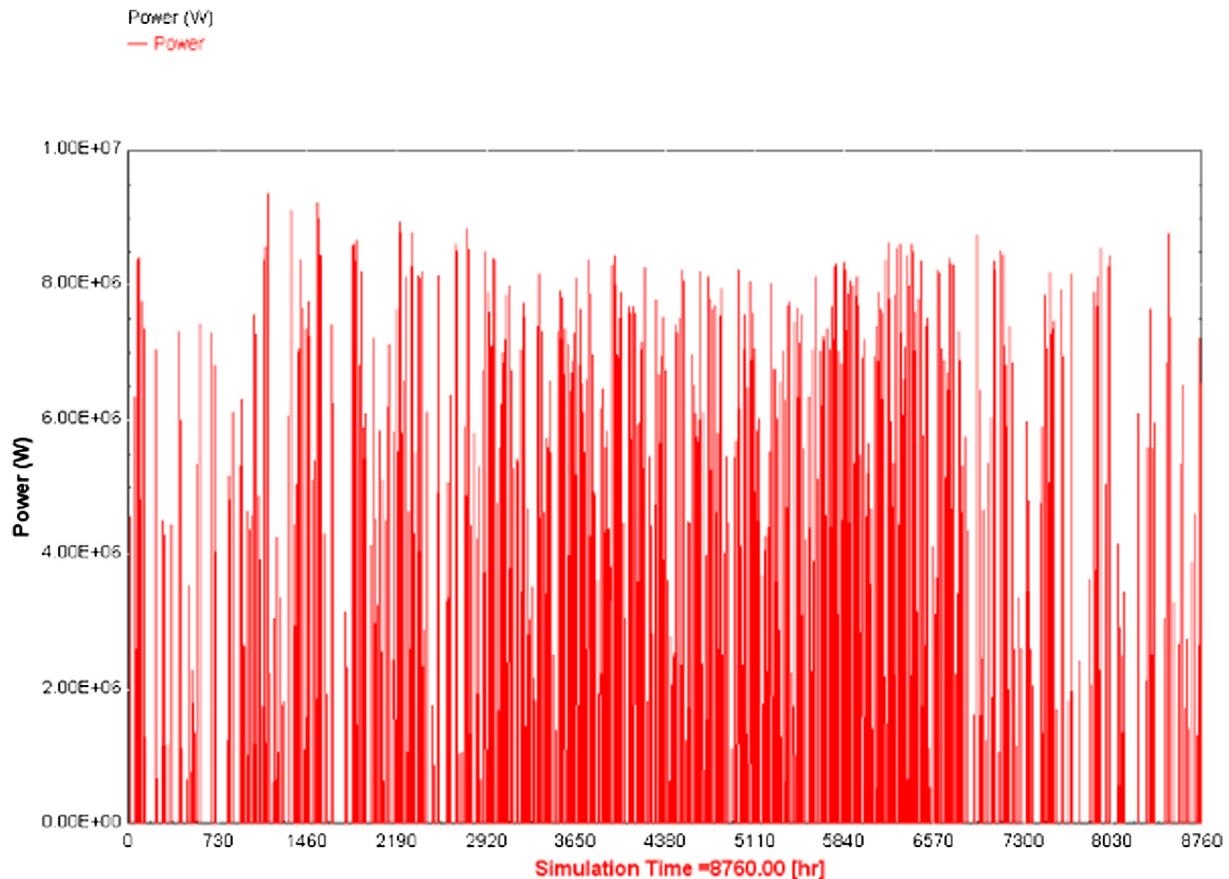


Fig. 6. Annual variation of net power output.

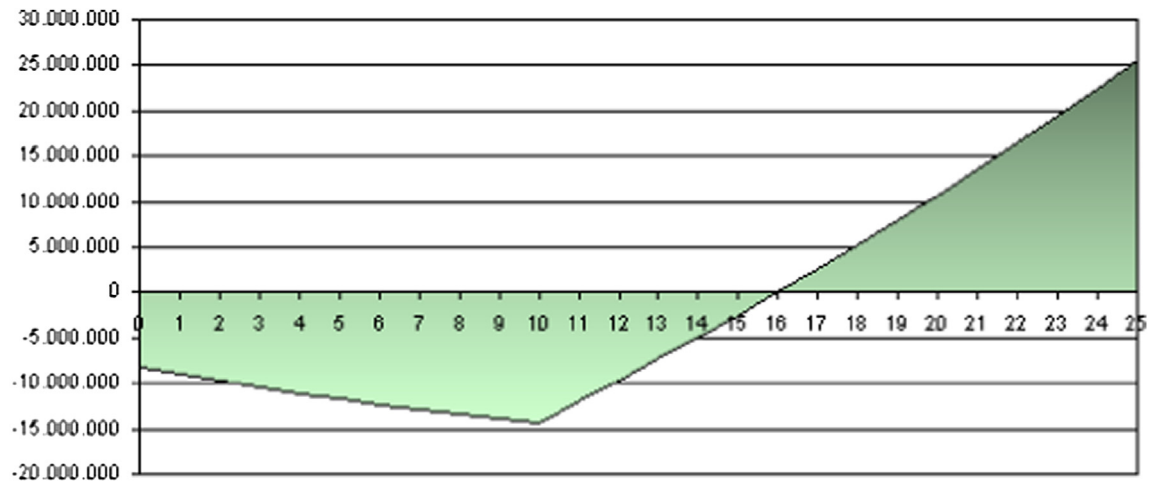


Fig. 7. Economic analysis [profit (€) vs time period (yr)].

globe. This program can generate TMY2 data files that are readable from TRNSYS weather data readers Type109-TMY2 and Type89d used in simulation. Specifically, weather data used in simulation include direct normal radiation, ambient temperature, wind velocity and solar zenith angle.

2.2.4. Economic data

The total installed cost, which is the project investment cost, is the sum of total direct cost and total indirect cost and is estimated to be about 27,000,000 €. Direct capital costs include costs for the collector and the power conversion unit, cost for the total solar field area of 250,000 m², and cost for necessary site improvements. It is calculated that total direct capital cost is about 21,500,000 €. Indirect capital costs, including costs associated with design and construction of the project and other costs like marketing costs and taxes, are estimated to be about 5,500,000 € [5]. Except for project's investment cost, which applies in year zero of the project, operation and maintenance cost is also required to be defined. Operation and maintenance costs represent annual expenditures on equipment and services that occur after the system is installed. According to financial analysis assumptions given by Greek government in order to evaluate potential concentrated solar thermal power plants, operation and maintenance costs are 115 €/kW annually. It is so estimated that annual expenditures for this kind of costs are 1,150,000 €. According to law, a fee of 3% over the electricity sales price is also applied. The electricity sales price (feed-in tariff) in Greece according to the power purchase agreement, which has a duration of 25 years, is 264.85 €/MWh. The loan is assumed to be 70% with a loan term of 10 years and a debt interest rate of 6%. The analysis period is assumed to be 25 years.

3. Results

The simulation results predicted that the system would produce 11.19 GWh annually, achieving a maximum power of 9.38 MW on February. The maximum monthly energy production predicted to be 1.54 GWh on September and the minimum 0.27 GWh on December. Table 1 presents the monthly energy production values.

Fig. 6 presents the net power output of the system for a simulation period of one year.

RETScreen software [7] was used for the financial analysis of the project. Based on electricity sales price of 264.85 €/MWh and annual production of 11.19 GWh, yearly income is expected to be 2,963,670 €. At the end of the analysis period of 25 years, total profit is expected to be 25,500,000 € while payback is achieved after 16 years of operation (Fig. 7).

According to the results, the 10 MW power plant is predicted to produce 11.19 GWh annually while an actual similar system of 9.5 MW, tested in Albuquerque of New Mexico, generated annually 16.49 GWh of net electric output [8]. Comparing the two results it can be seen that there is quite good agreement considering that the aggregate annual value of direct normal radiation in Albuquerque is estimated to be approximately 2500 kWh/m² [9] while in the location of the proposed power plant is estimated to be 1790 kWh/m².

4. Conclusions

Summarizing, a Dish/Stirling power plant with nominal power 10 MW is considered to be installed in Greek island Crete. It is well known that Greece is a country with abundant sunshine and Crete is one of the regions with the highest values of direct normal radiation. The simulation using TRNSYS software predicted annual energy production of 11.19 GWh. Evaluating the financial viability of the project, the assumption of 115 €/kW per year for operating and maintenance costs results in 1,150,000 € annually for the project of 10 MW. This cost is considered to be high compared to other studies and leads to payback period of 16 years and profit of 25,500,000 € after analysis period of 25 years. Assuming a cost of 75 €/kW per year for this kind of costs, payback period is predicted to be 13 years, while total profit at the end of the analysis period is 38,000,000 €.

Of all solar technologies, Dish/Stirling engine systems have demonstrated the highest solar to electric conversion efficiency of 31.25%. Therefore they have the potential to become one of the least expensive sources of renewable energy.

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